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Reconstruction of storm/tsunami records over the last 4000 years using transported coral blocks and lagoon sediments in the southern South China Sea

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Abstract

Large transported coral blocks on reef flats and elevated sedimentation rates in atoll lagoons were demonstrated to be excellent proxies for past strong storms/tsunamis in the southern South China Sea. Here we introduce another important proxy-coarse-fraction contents of lagoon sediments. This proxy is based on the principle that coarse fractions of enclosed lagoon sediments are usually controlled by strong sedimentary dynamics on the surrounding reef flat, and thus increases in the weight percentages of coarse-grained fractions of the lagoon sediments should also reflect strong storm/tsunami events or increases in storminess, with the size of the content peak as the proxy for the degree of storminess. Bearing this in mind, we measured the contents of the >1 mm grain-size fractions (referred to as "coarse-fraction content") in an undisturbed lagoon core precisely dated to cover the last 4000 years. The decadal-resolution data show a systematic variation, with some peaks strongly correlated with in timing with strong storm/tsunami events dated at AD 1872±15, 1685±8~1680±6, 1443±9, 1336±9, 1210±5~1201±4 and 1064±30 using wave-transported coral blocks. Using the mean coarse-fraction content (9.2%) for the entire core as a reference line, a total of 77 peaks were identified for the past 4000 years. Twenty of these peaks are higher than 23%, the mean value for peaks that are correlated in age with the six strong storm events identified using independently dated coral blocks. Among these >23% peaks, 13 occurred within the last 1000 years. The concentration of content peaks in the last millennium could be partially due to higher deposition rates and sampling resolution. Over the last ~4000 years there appears to be a weakly increasing trend in coarse-fraction contents towards present time, but this trend is not obvious within the last millennium. This long-term variation may be related to changes in both storminess and reef-lagoon morphology. However, the data do suggest three extremely stormy periods centring around AD ~1200, ~400 BC and ~1200 BC, respectively. Overall, this study demonstrates that combined use of transported coral blocks and coarse-fraction contents of lagoon sediments provides an excellent means for comprehensive reconstruction of past storm/tsunami activity.

1. Introduction

Catastrophic events (such as strong storms, typhoons, cyclones, hurricanes or tsunamis) have had a devastating impact on human lives and global economy, as well as on increasingly vulnerable ecosystem, as vividly manifested by the Sumatra earthquake and related Indian Ocean Tsunami on 26 December 2004 (Morrow and Llewellyn, 2006). The loss from extreme climatic events over the last decade has surged by 10 times relative to that of 1950s (see UNEP/GRID-Arendal library for graphics resources via http://www.maps.grida.no/go/graphic/global_costs_of_extreme_weather_events). Cyclones are predicted to generally increase in magnitude and frequency under scenarios of future climate change (Goldenberg et al., 2001; Emanuel, 2005; IPCC, 2007), despite some spatial variations, e.g. lower Atlantic hurricanes during the 1970–1980s (Webster et al., 2005; Nyberg et al., 2007). However, the knowledge of the past frequency and future trend of such extreme events is still very limited, mainly because historical records

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of such events are too short (usually <100 years) and sparse, and are limited to only a few countries like China with long civilization (Liu et al., 2001). Hence, there is an urgent need for reconstruction of such events in natural archives, especially those having occurred over the most recent few hundred to thousand years which are directly related to our present situation and the near future. A number of studies were carried out over the past 20 years to date and characterize storm/cyclone and tsunami events during Pleistocene and Holocene periods, using dating methods such as radiocarbon, thermoluminescence (TL) and electron spin resonance (ESR), combined with field geomorphological investigations (Bryant et al., 1992; Bryant et al., 1996; Nott, 1997; Hutchinson et al., 2000; Bryant and Nott, 2001; Nott and Hayne, 2001; Scheffers and Kelletat, 2003; Nott, 2004; Bondevik et al., 2005; Williams et al., 2005; Donnelly and Woodruff, 2007). Yu et al. (2004) first used thermal ionization mass spectrometric (TIMS) U-series method to date wave-transported coral blocks in the Nansha area, southern South China Sea and suggested that at least six strong storm/tsunami events occurred over the last millennium with an average 160-year cycle (ranging from 110 to 240 years). Comparing with the sand layers from coastal fen- or lake sediments, wave--transported coral blocks have the following advantages: (1) they can be easily dated to very high precision (with 2σ uncertainty up to 1–5 years for the age range of 0–1000 years) by U-series method; (2) they can accurately record the timing of such events by dating to their growth termination (i.e. the surface of the corals), because the mortality ages of coral blocks usually represent the times of such storm/tsunami events. For example, a massive *Porites* with a >2 m diameter was transported (and killed) by the Indian Ocean tsunami in Thailand on 26 December 2004 [see: http://www.planetsave.com/ps_mambo/index.php?option]. Some coral blocks up to 3 m in diameter were tossed onto the reef flat when Cyclone Fay passed Scott Reef (northwestern Australia) on 21 March 2004 (Gilmour and Smith, 2006). All such corals were still alive at the time of wave transportation. (3) Such coral blocks are widely distributed across tropical coral reefs and their sizes may provide information about the intensity of the wave events. However, the disadvantage in the use of transported coral blocks as an indicator of past wave events is that they can only provide a minimum estimate of the past storm/tsunami frequency because not necessarily all storms/tsunamis would result in transported coral blocks and some coral blocks may not have been alive at the time of such events. On the other hand, lagoons have a similar sedimentary environment, and often act as traps of storm/tsunami-related coarse-grained sediments like coastal lakes. Thus lagoon sediment cores have been successfully used to reconstruct hurricane activities in the Caribbean Sea over the past 5000 years (Donnelly and Woodruff, 2007). In addition, coral reef lagoon sediments usually contain short-lived branching coral fragments that can be precisely dated by the U-series method, providing a high-resolution chronology like that of the Yongshu reef lagoon core (Yu et al., 2006b). Thus in this study, we will demonstrate the importance of using combined lagoon sediment and transported coral block records for a better and comprehensive high-age-resolution reconstruction of storm (and possibly tsunami) history in the South China Sea. Although this method is demonstrated using South China Sea records, it can be widely applied to other parts of the world.

It is worthwhile to note that terminology such as storm, cyclone, typhoon and hurricane has been frequently used in different parts of the world, with typhoon being most likely being used in the South China Sea. In this study, we will use the word "storm" to represent all such terms, unless it is essential to use the other terms.

2. Study site and environment

Yongshu Reef (9°32′–9°42′N, 112°52′–113°04′E; see Fig. 1a, b) in the southern South China Sea is an open spindle-shaped atoll (about 25 km long in NEE–SWW direction and 6 km wide in NW–SE direction) and covers an area of about 110 km^2 (Yu et al., 2004). A closed lagoon (about 380 m long, 150 m wide and maximum 12 m water deep) is situated in the centre of the southwest reef flat, which is about 0–2 m under low tidal. The area around the lagoon is referred to as the "small atoll" (Fig. 1c). It stands over 2000 m above the sea floor and is far away from mainland, and therefore it is relatively undisturbed by human activity. Because of this and other evidences from its geomorphology, tectonics and reef developing process, the large coral blocks standing on the southwest area of this small atoll were inferred as indicators of past strong storms, and storm events occurred at AD 1064$\pm$30, 1210$\pm$5~1201$\pm$4, 1336$\pm$9, 1443$\pm$9, 1685$\pm$8~1680$\pm$6, 1872$\pm$15, respectively, were further identified (Yu et al., 2004).

Six biogeomorphological zones are recognized for this small atoll (Yu et al., 2004). From outer to inner zones, these are (1) reef-front living coral zone, (2) outer reef-flat coral zone, (3) reef-ridge coral-branch-cemented zone, (4) inner reef-flat branching-coral/sand zone, (5) lagoon slope branching-coral/fine-sand zone and (6) lagoon basin-floor silt zone. Sands originated from reef organisms are the dominant material on the surface of the reef. The mean grain size of the sands varies from 0.7 to 0.8 mm on the reef flat, through 0.5–0.7 mm on the lagoon slope to 0.15 mm on the lagoon basin floor, showing a decreasing trend with increasing water depth (Yu et al., 1997).

Detailed climatic data from the National Bureau of Meteorology of China (http://www.nmc.gov.cn/), including wind (direction and speed), air temperature, typhoon (frequency and intensity), sea surface temperature, rainfall, sunshine duration, surface salinity and surface water current, of this reef were described in the previous paper (Yu et al., 2004). From June to September, the area is under the influence of southwest monsoons with an average